Main Injector Intensity Limitations at Transition

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Talk presented at the

TEV33 MEETING OF September 29, 1997

Abstract

We have carriedout calculations to establish beam intensity limitations in the Fermilab Main Injector at transition. Simulations have been performed using computer code ESME to understand longitudinal beam dynamics at near transition (~ +/- 50 msec around transition) by spanning wide range of parameters like longitudinal emittance, Z/n, bunch intensity etc. We find that bunches with,

6×10^{10} ppb $\varepsilon_l > 0.12$ eV-sec

10×10^{10} ppb $\varepsilon_l > 0.20$ eV-sec <-- from slip stacking

15×10^{10} ppb $\varepsilon_l > 0.25$ eV-sec

can be accelerated with the standard phase jump scheme in the Main Injector with out any beam loss or noticeable emittance growth.

Introduction

The Main Injector (MI) is a high intensity 150 GeV proton synchrotron. This accelerator replaces the existing Main Ring for collider operation of the Tevatron and has an additional capability of providing 120 GeV proton beam year round, for the fixed target experiments like NuMI and experiments in the Switchyard area [1]. Presently, it is planned to accelerate the proton beam from 8 GeV to 120 GeV in MI through a transition gamma of 21.838 using standard phase jump scheme. Originally it was planned to go through transition at a rate of dp/dt~ 168 GeV/c/sec. But our preliminary studies indicated that by increasing dp/dt by about 60-70% (without any additional cost on building dipole power supplies) the transition can be made smoother and we will be able to accelerate higher intensity beam through transition in the Main Injector.

In the work presented here we first outline the anticipated problems around transition crossing in Main Injector and their contributions to emittance growth or beam losses. Secondly results of our computer simulations using ESME for similar situations. The computations have been carriedout with realistic machine parameters. Measured values of parameters are appropriately modeled in the simulation (For example, analytically calculated beam pipe cut off frequency is 2.2 GHz, while measured valued is 1.502 GHz. Therefore we take later value in our simulations. Also an effective circular beam pipe radius of 58 mm). The lower limits on the beam longitudinal emittance (A or εl) for a given number of particles in a bunch (N) is determined by the negative mass instability limits. In all of the calculations we use FFT bins of 512 which corresponds to 13.6 GHz for microwave cutoff.

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- # Introduction
  - MI Operating Parameters
  - MI Operating cycles
- # Anticipated Transition Crossing Problems in MI
- # Simulations of Transition Crossing using ESME
  - ESME (General overview) and Comparison with MR data
  - Simulations for MI
- # Summary and Conclusions

Summary and Conclusions

\# We have studied the transition crossing problems for different operating scenarios of the Main Injector.
Suggestions were made to increase dp/dt from ~168GeV/c/sec to ~280GeV/c/sec to make transition crossing smooth.

\# Longitudinal beam dynamics simulations have been performed using ESME to estimate beam intensty limits through transition. The calculations were done including : a) **space charge effects** and b) **broad band impedance.**
We find that bunches with,

6×10^{10} ppb $\quad \varepsilon_l \gtrsim 0.12$ eV-sec
10×10^{10} ppb $\quad \varepsilon_l \gtrsim 0.20$ eV-sec <-- from s.s.
15×10^{10} ppb $\quad \varepsilon_l \gtrsim 0.25$ eV-sec

can be accelerated with the **standard phase jump scheme** in the Main Injector

\# More calculations will be done with the time domain version of the ESME (being written by Jim).

\# There are number of issues to be addressed regarding acceleration of high intensity beam bunches in the MI. They are :

a) Coupled bunch instability excited by higher order modes in the MI (MR) rf cavities. This can be studied with ESME. Very important !!
b) Beam loading, RF power etc.

MOTIVATION

The design beam intensity of the Main Injector with
Normal Transition Phase Jump at Transition =

6×10^{10} particles/bunch

(3×10^{13} particles/MI batch)

(Ref. MI Design Hand Book 1994)

With slip stacking the expected beam Intensity =

$10\text{-}12 \times 10^{10}$ particles/bunch

($5\text{-}6 \times 10^{13}$ particles/MI batch)

(Ref. S. Holmes, March 1997 Workshop on Fixed Target programs at MI)

We like to achieve MI beam Intensity =

$>15 \times 10^{10}$ particles/bunch

($>7.5 \times 10^{13}$ particles/MI batch)

Question :

Could transition crossing be a problem in MI ?

What are the limiting conditions ?

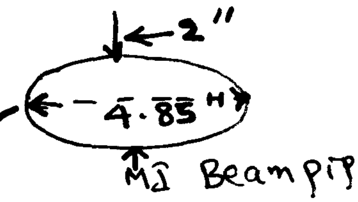
Table I. The Main Injector parameters.

Mean radius of FMI	528.3019 m
γ_t (nominal)	21.838
$\dot{\gamma}_t$	167 - 267 sec^{-1}
α_1^a	0.002091
Maximum RF Frequency and RF Voltage	4 MV for 53 MHz 15 kV for 106 MHz 60 kV for 2.5 MHz 15 kV for 5 MHz
Protons ϵ_l at 8 GeV Injection I_{Bunch} at 8 GeV	 0.1–0.35 eVs 6–15 $\times 10^{10}$
Anti-protons ϵ_l at 150 GeV Injection I_{Bunch} at 150 GeV	 3–4 eVs 5–7 $\times 10^{10}$
Coup. imp. $Z_{\|\|}/n$	3 Ω
Beam pipe wave guide	1.5–2.2 GHz cutoff
cutoff frequency Transverse Beam size(a)	 2.2 – 5 mm
Beam pipe Radius (b)	5.8 cm (m)

$\alpha_J \Rightarrow 0.996$

1.6 Ω W. Chou

Effective



[a] α_1 is the second order term in the expansion of path length.

Non-linear time $T_{nl} = 0.6$ msec

Non-adiabatic time $T_{na} = 2.1$ msec

$\epsilon = 20\pi$ beam

$$a = \sqrt{\frac{\beta\epsilon}{6\pi\gamma} + D\left(\frac{\Delta p}{p}\right)^2}$$

$\langle\beta\rangle \sim 50$ m

$\gamma = \gamma_t$ $\quad a = 5$ m

$\langle D\rangle = 1$ m

$\frac{\Delta p}{p} \simeq 0.005$

Table 1. Main Injector Impedance Budget

Component	Number	Impedance	
		$Z_{\parallel}/n$ (Ω)	$Z_{\perp}$ (MΩ/m)
RF cavities (HOM)		0.09	0.023
Main cavities (53 MHz)	18		
Coalescing (2.5 MHz)	5		
Coalescing (5 MHz)	1		
2nd harmonic (106 MHz)	1		
Transitions (tapered)		0.012	0.01
RF section	10		
Inj section	2		
Bellows (shielded)	552	0.37	0.67
Flange gaps (shielded)	552	-	-
Weldments	2208	0.001	0.005
Gate valves (shielded)	34	0.04	0.05
Pump ports (screened)	577	0.1	0.07
Beam position monitors	208	0.18	0.3
Kickers		0.3	0.6
p inj (1.1 m)	3		
$\bar{p}$ inj/p extr (2.24 m)	2		
$\bar{p}$ extr (2.2 m)	2		
Abort (2.2 m)	2		
Lambertson laminations		0.1	0.3
Lambertson joints		0.3	0.1
Lambertson-quad	12		
Lambertson-Lambertson	6		
Lambertson-dipole tube	10		
Resistive wall		0.11	0.092
Total		1.6	2.2
Instability threshold:			
At 8.9 GeV/c		39	7.9
At 120 GeV/c		8.0	16

Main Injector Operation Cycles and Baseline Beam Intensities

Operation Mode	Number of Booster Batches	Energy (GeV)	Cycle (sec)	Proton /cycle	proton /bunch
Antiproton Production	1	120	1.5	5E12	6E10
Fixed Target Injection	6	150	2.4	3E13	"
Collider Injection	1	150	4.0	5E12	"
High Intensity slow spill	6	120	2.9	3E13	"
High Intensity fast spill (NuMI Intensity)	6	120	1.9	3E13	"

Anticipated Problems during Transition Crossing in a proton Synchrotron

A. Non-adiabatic Time

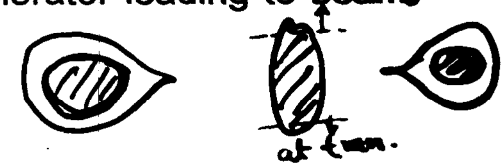
During acceleration across the transition energy, there excist a **time** interval where the **synchrotron oscillations of the particles in a bunch are FROOZEN.** This time iinterval is called as **non-adiabatic period *Tna* which is** given by,

$$T_{na} = T_s \left[\frac{f_s E_0 \gamma_T^4}{4\pi h \dot{\gamma} e V_{rf} |\cos\phi_s|} \right]^{1/3} .$$

Tna = 2.1 msec

During this time the leading and the lagging paticles in a bunch remain in their relative position, while they continue to gain or loose energy from the RF cavity. As result of this momentum spread increases very rapidly, and may exceed the momentunm aperture of the accelerator leading to beam loss.

$\left.\frac{\Delta P}{P}\right|_t \simeq 0.2\%$ in MI beam $< 2\%$.



B. Johnsen's Effect and Non-linear Time

Different beam particles in a bunch cross transition at different times. Therefore depending on their momentum spread, a particle with peak momentum $\hat{\delta}$ crosses transition earlier than synchronous particle by a time period ***Tnl*** given by,

$$T_{nl} = \frac{\gamma_T \hat{\delta}}{\dot{\gamma}} \left(\alpha_1 + \frac{3\beta_s^2}{2} \right) .$$

$$\hat{\delta} = \left.\frac{\Delta P}{P}\right|_{max}$$

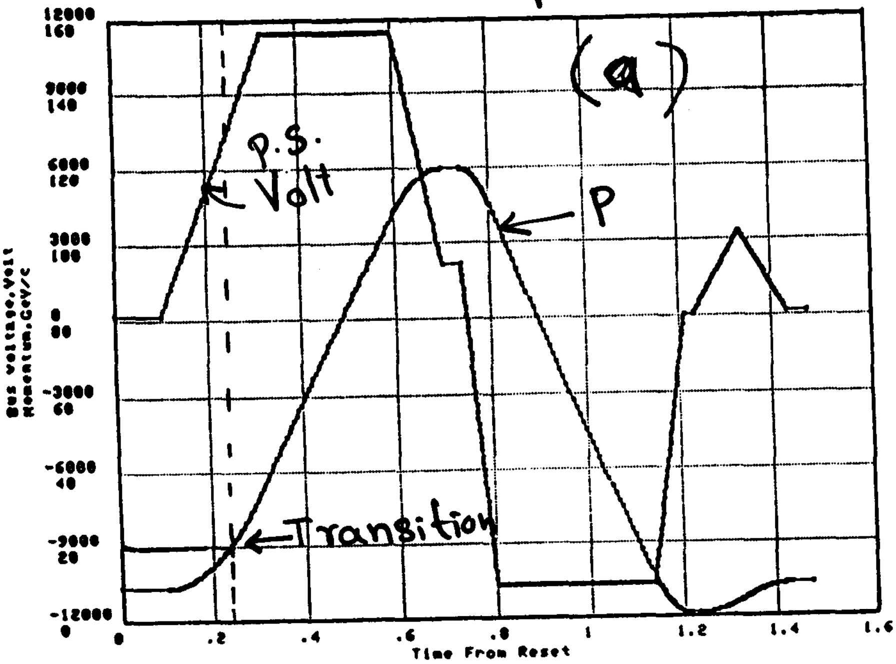
Tnl = 0.6 msec

As a result of this the particles in the head and the tail of a bunch **will be** subjected to <u>non-linear force and they follow hyperbolic divergent path</u>. This leads to effective emittance growth in the longitudinal phase space.

Main Injector

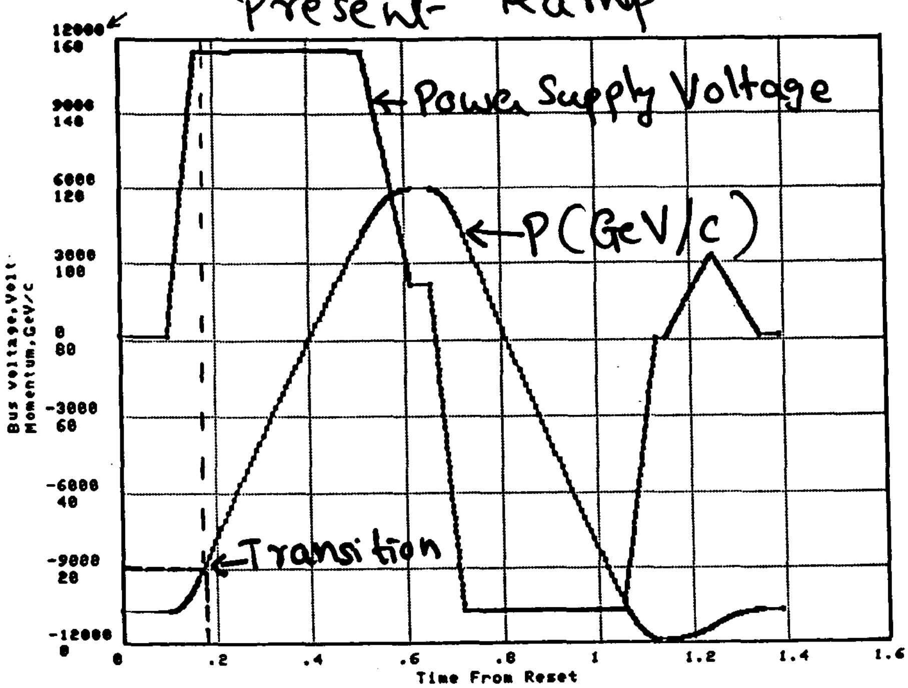
Old Ramp scheme

$$\left.\frac{dp}{dt}\right|_{tran} \approx 168 \frac{GeV}{c\text{-sec}}$$



Present Ramp

$$\left.\frac{dp}{dt}\right|_{tran} = 280 \frac{GeV}{c\text{-sec}}$$



C. Microwave Growth

The growth of microwave amplitudes across transition is unavoidable because for certain length of the time the frequency slip parameter $\eta = 1/\gamma_t^{\,2} - 1/\gamma^2$ is too small to provide enough frequency spread for Landau damping.

D. Umstatter's Effect

This is a transverse effect. The transverse space-charge force will lower the betatron tune of the particles at transverse edge of the bunch near the center and lower the transition γt. These particles cross transition earlier than the synchronous particles.

The depression of γt is given by,

$$2\gamma_t \Delta\gamma_t = -\varepsilon\lambda(0) \; ,$$

where

$$\lambda(0) = \frac{N}{\sqrt{2\pi}\,\sigma_\tau h\omega_0}$$

h_v = Half height of vacuum chamber.

is the linear density at the center of the bunch and

$$\varepsilon = \frac{4hr_pR}{\beta_t^2\gamma_t^3}\left[\frac{1}{a(a+b)} - \frac{\epsilon_1}{h_v^2}\right]$$

a & b are H & V- beam sizes

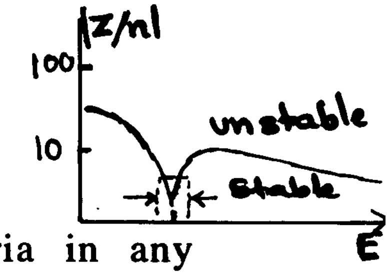
ϵ_1 = Electrostatic Image Coef. for rectangular Beam Pipe.

<u>**Therefore some particles at the center of the bunch will cross transition at time $\Delta T = \Delta\gamma t / (d\gamma t/dt)$ = 0.04 msec earlier than synchronous particle. Since this is much smaller than T_{na} = 2.1 msec Umstatter effect should be negligible in the Main Injector**</u>

C. Microwave Growth

The Microwave instability limit for bunched beam with a Gaussian momentum distribution in the presence of a broad band resonator is given by **Keil-Schnell criteria**

$$\left|\frac{Z_{\parallel}}{n}\right| < F_1 \frac{2\pi|\eta|(E/e)}{I_p} \beta^2 \left(\frac{\sigma_p}{p}\right)^2$$



Except near transition, this is most restrictive criteria in any circular machine. In the case of Main Injector the limits are,

Z||/n = 37 Ω at injection
Z||/n = 6.6 Ω at 150 GeV

The growth of microwave amplitudes across transition is unavoidable because for certain length of the time the frequency slip parameter

$$\eta = 1/\gamma_t^{\,2} - 1/\gamma^2$$

is too small to provide enough frequency spread for Landau damping. Thus, the stability diagram obtained from Keil-Schnell is not applicable very near to the transition energy; during a time interval of $-t_0$ to $+t_0$ one expects microwave instability growth, where,

σ_τ = Max. RMS. Bunc Length.

$$t_0 = \frac{F_2 e N (Z/n)\gamma_t^4}{\omega_0 V_{rf} \sin\phi_0} \frac{(E_0/e)^2 \sigma_\tau}{(A/e)^2}, \quad = \frac{1}{3^{5/6}\Gamma(1/3)} \sqrt{\frac{A T_{na}^2 \dot{\gamma}}{E_0 \beta_t^2 \gamma_t^4}}$$

$= 0.17$ m

This is about **1.25 msec** smaller than non-adiabatic time period of MI. Notice that this quantity varies as (N . σ_τ / A^2). The Instability growth [redacted] is given by,

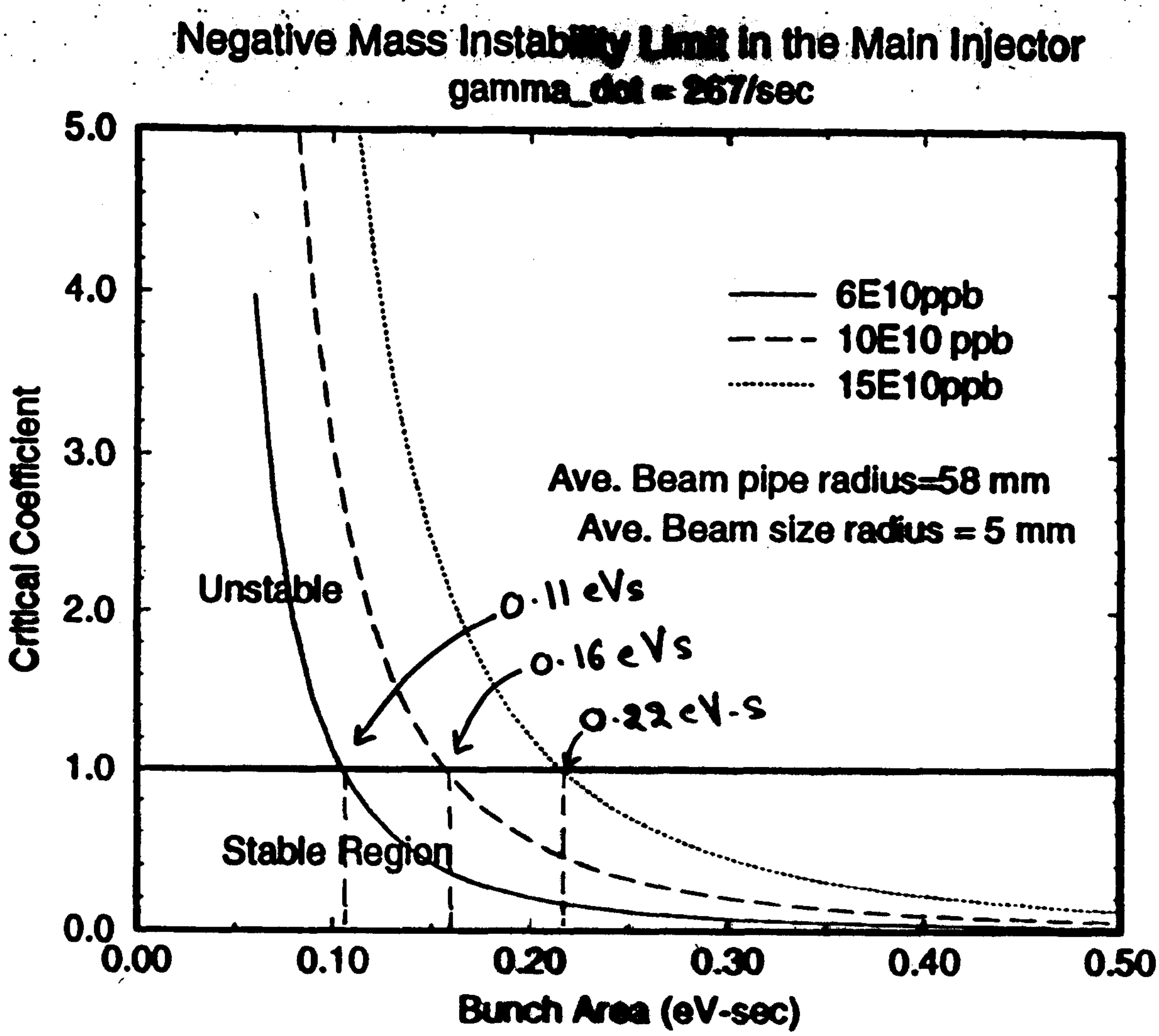
$$e^{(S_b + S_a)}$$

$\simeq 1.82$ @ $Z/n = 3\,\Omega$

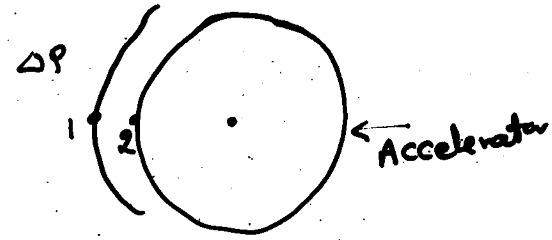
where

$$\frac{S_b}{n} = \frac{S_a}{n} = \frac{F_1 [eN(Z/n)\gamma_t^2]^2}{V_{rf}\sin\phi_0} \frac{(E_0/e)^2 \sigma_\tau}{(A/e)^3},$$

$\sim N^2/A^{2.5}$ — Non-linear



Negative Mass Instability Limit in the Main Injector
gamma_dot = 267/sec
Critical Coefficient
Bunch Area (eV-sec)
5.0
4.0
3.0
2.0
1.0
0.0
0.00
0.10
0.20
0.30
0.40
0.50
6E10ppb
10E10 ppb
15E10ppb
Ave. Beam pipe radius=58 mm
Ave. Beam size radius = 5 mm
Unstable
Stable Region
0.11 eVs
0.16 eVs
0.22 eV-s



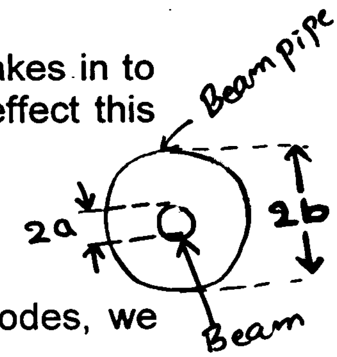
E. Negative Mass Instability

If two particles in a proton synchrotron have slightly different energy then they will be having different angular velocities $\omega = v/R$. But which will be having larger angular velocity depends up on whether $\Delta v/v$ is greater or smaller than $\Delta R/R$ because

$$\Delta\omega/\omega = \Delta v/v - \Delta R/R$$

If $\Delta v/v$ is greater then faster particle will be having larger ω . Othervise the slower particle will be having larger ω. In a strong focusing machine, below transition energy $\Delta v/v > \Delta R/R$ and above $\Delta v/v < \Delta R/R$. Thus if a particle is accelerated forward it will move backwards - as though the particle has **negative mass**. Under certain circumstances the situation gets unstable. This is instability is called **Negative Mass Instability.**

W. Hardt has proposed a theory of negative-mass blowup that takes in to account of Landau damping. In the presence of space charge effect this becomes significant. The growth has maximum at



$$k_C = k_{1/2} / \sqrt{3} \quad \text{where } k_{1/2} = \gamma R\,(1.6/b + 0.52/a)$$

For **Main Injector k_C = 79.2 GHz.** After summing all the bunch modes, we have,

$$\xi k_{\text{eff}} \left(\frac{r_p}{R}\right)^2 \left(\frac{E_0^{5/2}}{h^{1/3}\omega_0^{4/3}\gamma^{2/3}}\right) \left(\frac{N_b^2 g_0^2 |\tan\phi_s|^{1/3}}{A^{5/2}\dot{\gamma}^{7/6}}\right) = cE_c\ ,$$

ξ - is a constant.

The quantity E_C is given by,

$$E_c = \frac{1}{2}\left[\ln N_b - \ln\left(\frac{k_{b\frac{1}{2}}\sqrt{8\pi}}{3\sqrt{\frac{1}{2}\ln N_b}}\right)\right]\ ,$$

where $k_{b\ 1/2} = k_{1/2}\,\hat{\phi}\ /\pi h$ and $k_{eff} = 3\ /3\,k_{1/2}\ /16$. **When the critical coefficient c < 1, there is no negative mass instability.**

Since the ESME simulations carried out here do not cover high frequency range, <u>we examine the only the (N_b,A) region which is below the negative mass instability limit.</u>

What ESME Can Do ? and its input paramters

ESME is a Computer code used to simulate longitudinal beam dynamics in circular machine. Tracking of the particles is performed in **frequency domain**.

Author : Jim MacLachlan, developed at Fermilab

This program is widely used by other high energy physics Labs : Fermilab, CERN, KEK, Brookhaven ...

Input parameter :

Accelerator parameters - circumferene, γ_t, higher order correction to momentum compaction, scraping radius , beam pipe radius, etc.,

Ramp curve + RF features,

Bunch Properties : Bunch emittance, Particles distribution types, # of particles/bunch, transverse size of the beam.

and Many more ...

Features of the Program :

Number of Macro-particles and # of FFT bins -- limitted by computer merory and time

1 M -part
t_{Track} = 80 ms
CPU ≃ 6-8hr.

Evolution of the phase space distribution of particles in longitudinal
- ~~space~~ without and with space charge forces
- RF phase and volatge feed back included
- Broad Band and narrow impedances included
- RF gymnastics: addition of several RF wave forms

Features of the Program :

Standard output - phase space + other description at any stage of the comutation, Nice graphical outputs, history, FFT details, Mountain Range picture, etc.,

Negative Mass Instability Limit for MI

(Normal Transition Phase Jump)

Beam Intensity	Limits on ϵ_l		
	$a = 2.3$ m $b = 39.4$ mm	$a = 3$ mm $b = 39.4$ mm	$a = 5$ mm $b = 58$ mm
6×10^{10} ppb	≥ 0.17	≥ 0.14	≥ 0.11
10×10^{10} ppb	≥ 0.24	≥ 0.20	≥ 0.16
15×10^{10} ppb	≥ 0.33	≥ 0.27	≥ 0.22

ESME calculation : $\epsilon_l = 0.25$ eV sec

$I_b = \leq 15 \times 10^{10}$ ppb

B. Collective Behavior of the Particles

In a synchrotron, a trun-by-turn tracking of the longitudinal motion of the beam can be used to study beam-induced forces. In this case **any effect which influences the single particle motion is considered as a collective phenomina.**

ESME is capable of modeling following types of collective effects:

a) Space charge and the reaction of the beam environment

b) Feed back system (e.g., from bunch centroid to the RF phase or bunch width to RF amplitude).

In all these cases only the effect on <u>longitudinal dynamics</u> is modeled. All these are treated in **Frequency domain.**

<u>Space Charge and the Reaction of the Beam Environment :</u>

The beam is modeled as a cylinderical charge distribution of constant radius "a" centered in a cylindrical vacuum chamber of perfect conductor of radius "b". The particles in a bunch may be modeled to have one of the **15 built in distributions**.

For relativistic particles in a smooth cylindrical beam pipe, the longitudinal electic space charge field is given by ,

$$E_s(s) = -[1 + 2\log(b/a)]\frac{\lambda'(s)}{4\pi\varepsilon_0\gamma^2}$$

where $\lambda'(s)$ is derivative of longitudinal line charge distribution.

The longitudinal impedances can be of two types:

i. A simple resonance for which it is sufficient to specify three parameters viz., frequency, strengh and width.

ii. User specified table of complex longitudinal impedance at different frequencies $Z_{||}(\omega)$.

Description of the ESME Code

A. Single Particle Dynamics

In the heart of ESME there is a pair of single particle difference equations

$$\begin{aligned}\theta_{i,n} &= \left[\frac{\tau_{s,n-1}}{\tau_{s,n}}\theta_{i,n-1} + 2\pi\left(\frac{\tau_{i,n}}{\tau_{s,n}} - 1\right)\right] \\ E_{i,n} &= E_{i,n-1} + eV(\phi_{s,n} + h\theta_{i,n}) - eV(\phi_{s,n})\end{aligned}$$

h is the harmonic number

s and ***i*** denote quantities related to the synchronous and particle to the ***i*** th particle

$\tau_{\mathbf{n}}$ is the synchronous period at turn **n**

$\Theta_{\mathbf{n}}$ is the azimuth angle of the particle and $\mathbf{E_n}$ is the energy of the particle

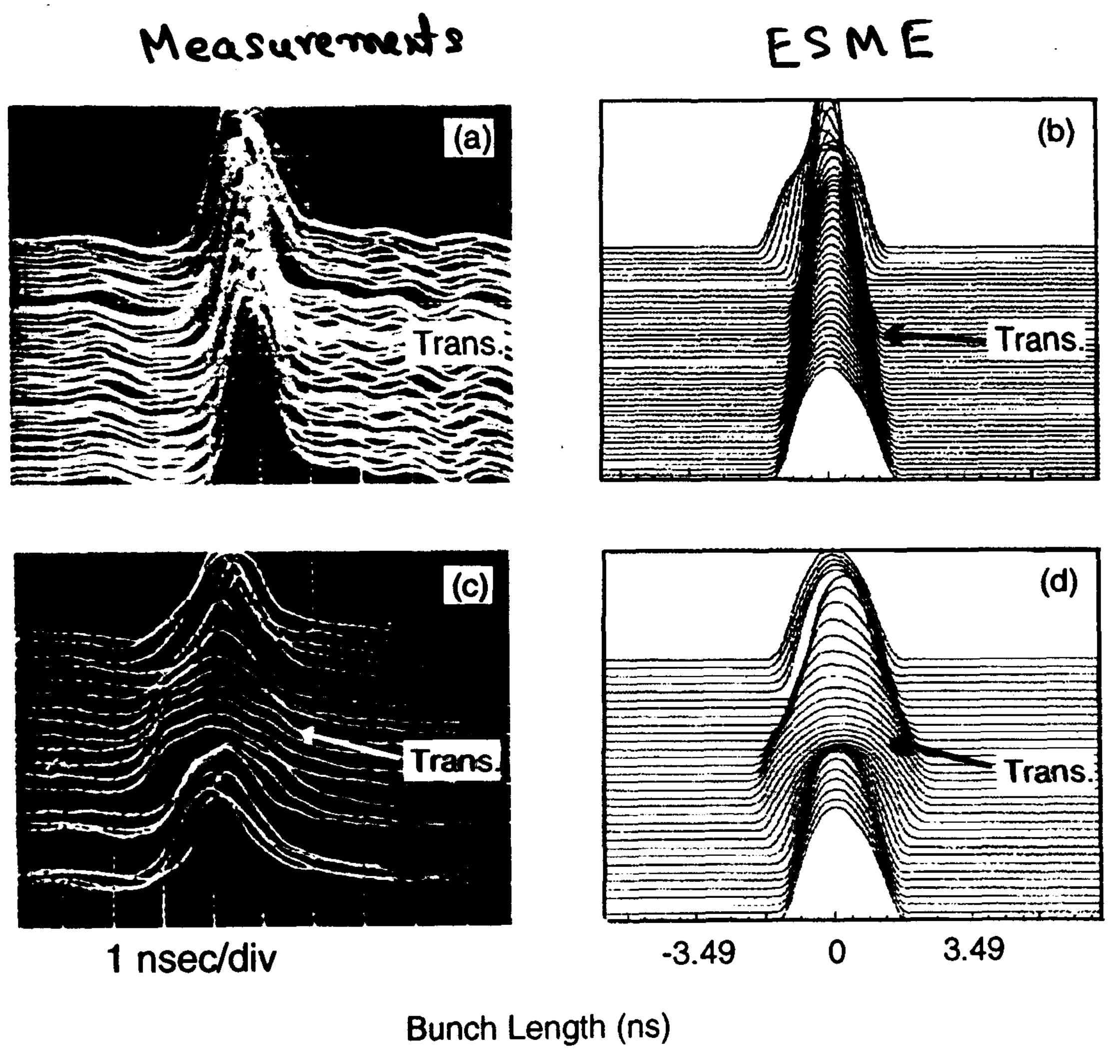
Coupling between the transverse and longitudinal dynamics enters into the simulations only through the relation

$$\tau_{i,n} = L_{i,n} / c\,\beta_{i,n}$$

The dependence of the orbit path length L on the momentum is set by externally specified coefficients of the series expansion of L in powers of $\Delta p_i / p_o$ as

$$L = L_0\{1.0 + \alpha_0\,\delta + \alpha_0\,\alpha_J\,\delta^2\}$$

where α_0 is the momentum compaction factor and α_J is the Johnsen's parameter.



Bhat, et al., Phys. Rev. E (1997) Vol. 55, Page 1028

Present Simulations :

In the present calculations the impedance, $\mathbf{Z_\omega}$ seen by a single Fourier component of the beam current at a frequency "ω **/2**π" taken as,

$$\frac{Z_\omega}{n} = -j\frac{Z_o g}{2\beta\gamma^2} + \frac{Z_W}{n},$$

where the first term in the impadence is due to space-charge, Z_W is the total wall impedance of the accelerator. $\mathbf{Z_o = 377\ \Omega}$ (impedance of the free space) and

$$g = 1 + 2\, ln\ (b/a)$$

We approximate the Z_W to the **Longitudinal Broad Band Impedance** which is given by,

$$Z_{\|}(\omega) = \frac{R_s}{1 + jQ(\frac{\omega_c}{\omega} - \frac{\omega}{\omega_c})}.$$

where ω_c is the beam pipe cut-off frequency.

For the Main Injector beam we take

Cut- off frequency f_C = 1.5 GHz — Measured value is 1.506 GHz. by Ed.

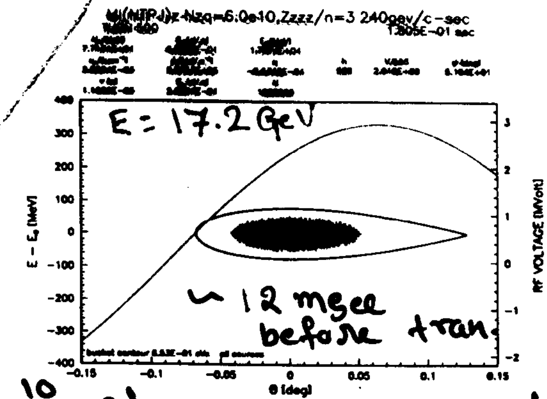
Average beam size **a = 0.005 m**, Beam pipe Radius **b = 0.058 m**

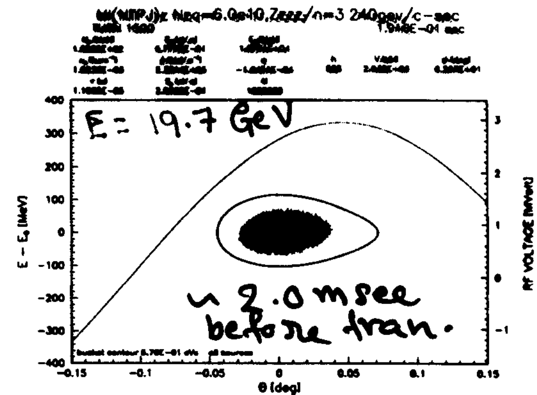
Line Charge Distribution = **Parabolic**

Typical Number of macro particles used = **1M**

Number of FFT bins = **512** => 13.5 GHz microwave cut-off

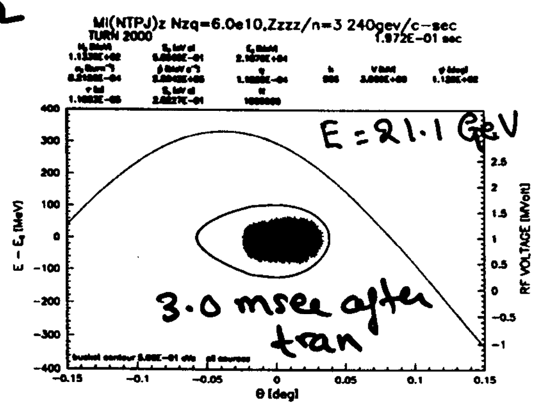
Coupling Impedance $\mathbf{R_S = 3\ \Omega}$ — Estimated value is 1.6 Ω by W. Chou

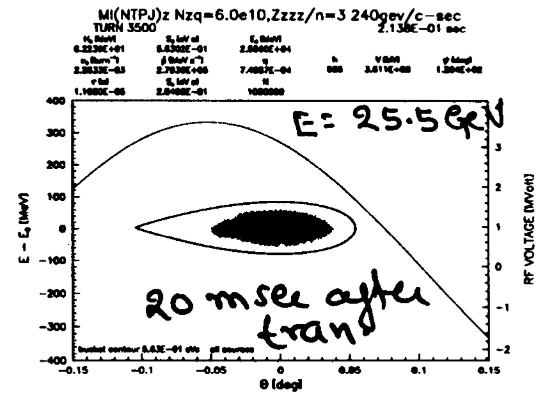


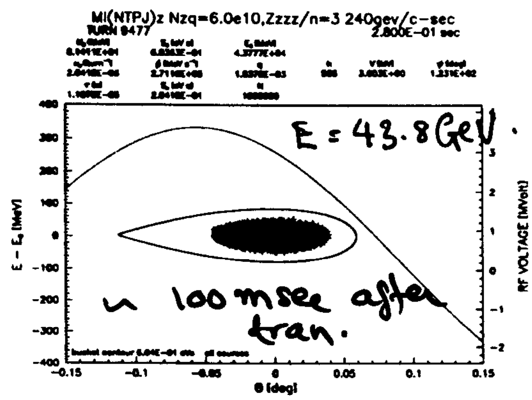


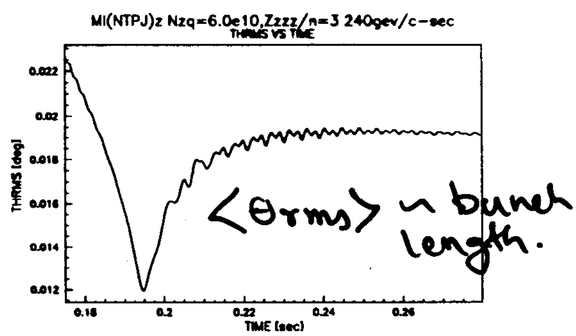
$I = 6 \times 10^{10}$ ppb $\epsilon_l = 0.2$ eVsec ; with phase feed back

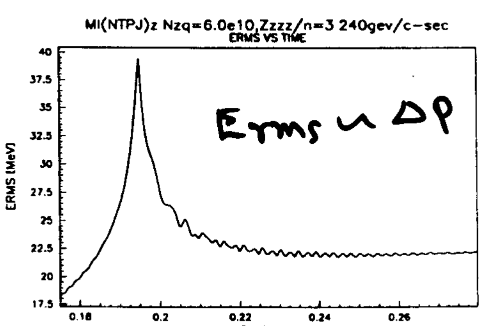
$z/n = 3\,\Omega$

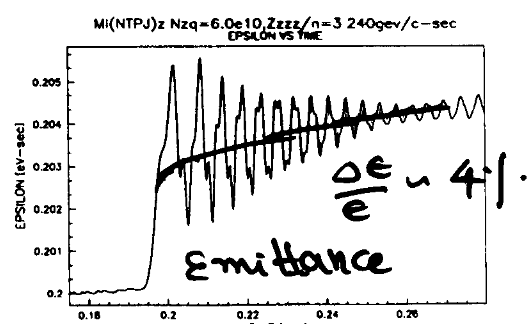




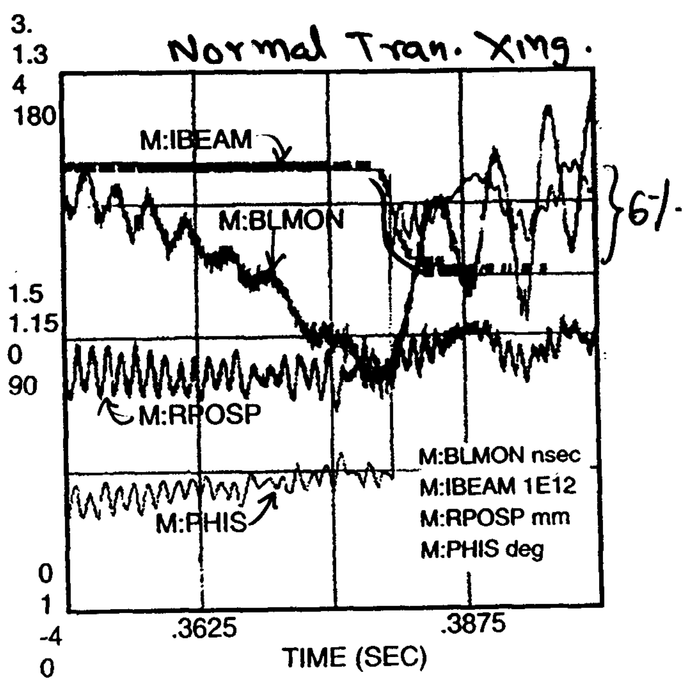


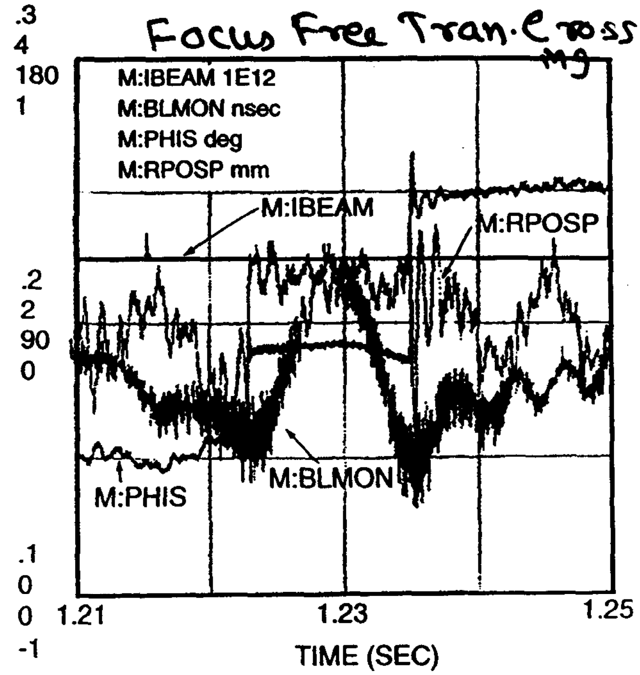


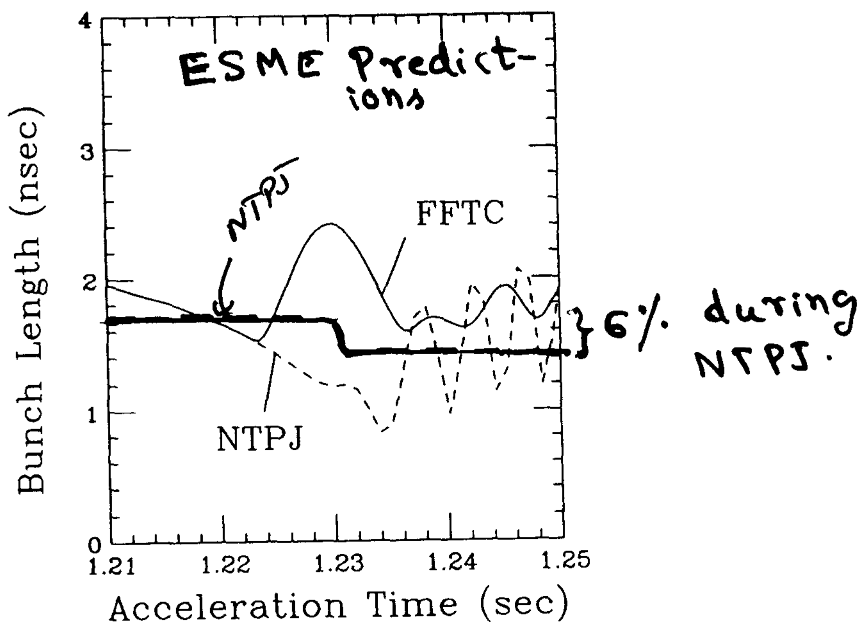




Main Ring







$$\frac{\Delta R}{R} = \frac{1}{\gamma_t^2}\frac{\Delta p}{p}$$

$\frac{\Delta p}{p} = 0.3\%$

$\gamma_t = 18.85$

$R = 1000\ m$

$\Delta R = 0.0082\ m$

Beam pipe radius (scraping) = 0.004 m

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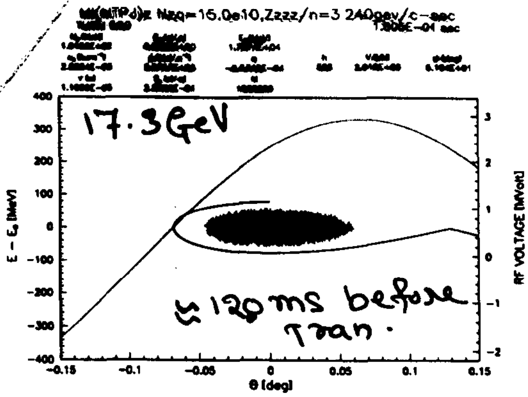
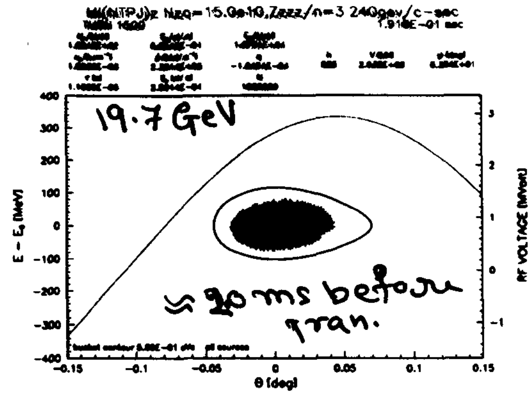
$I = 15 \times 10^{10}$ ppb

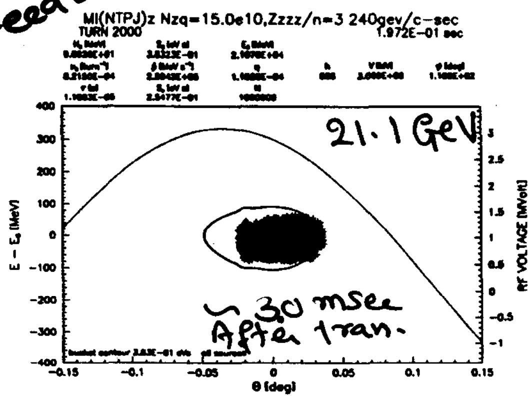
$Z/n = 3\ \Omega$

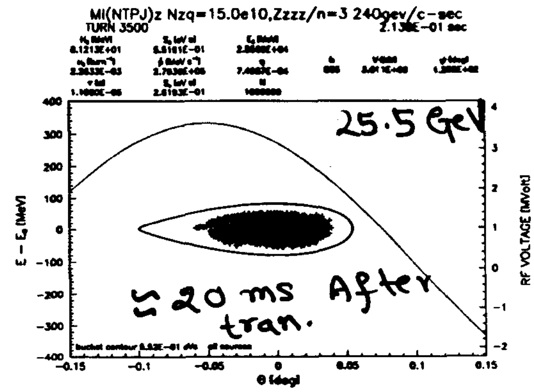
$\epsilon_L = 0.25$ eV-s

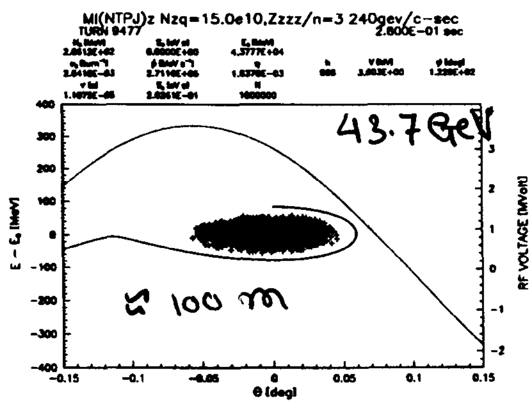
with Phase Feedback

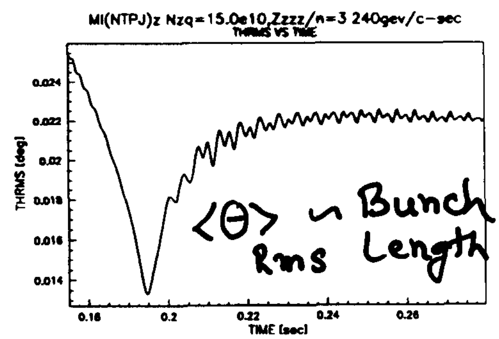


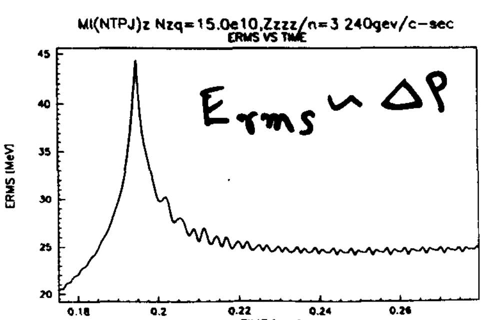


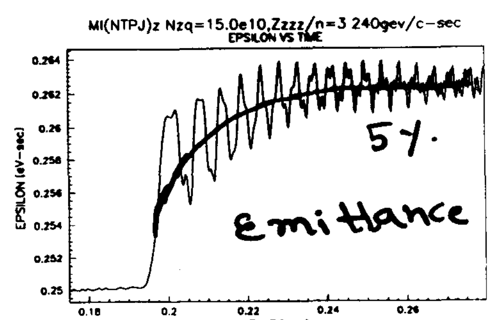


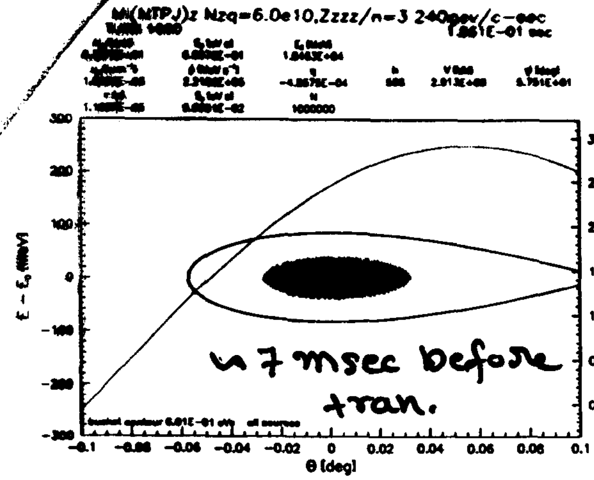


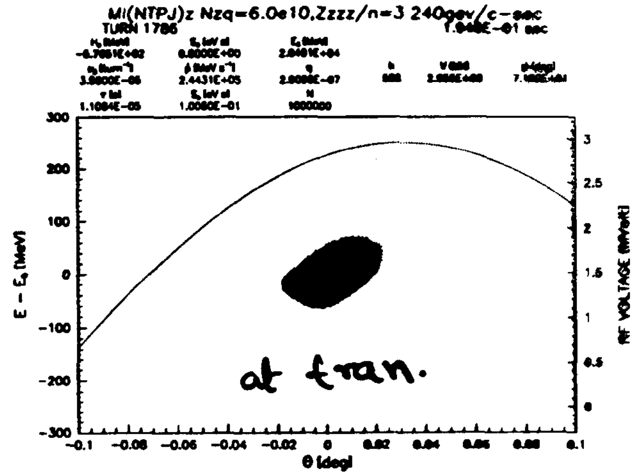






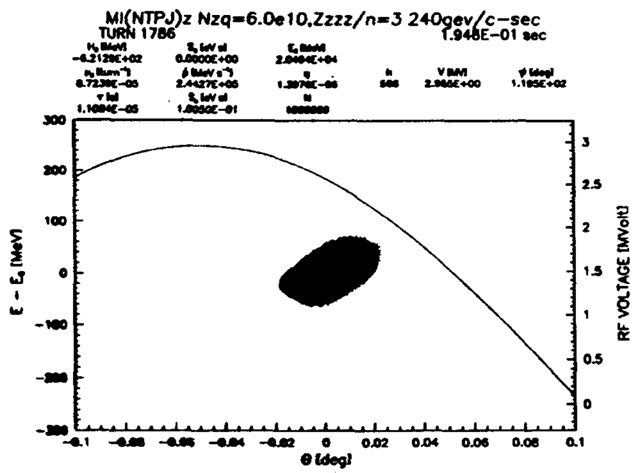


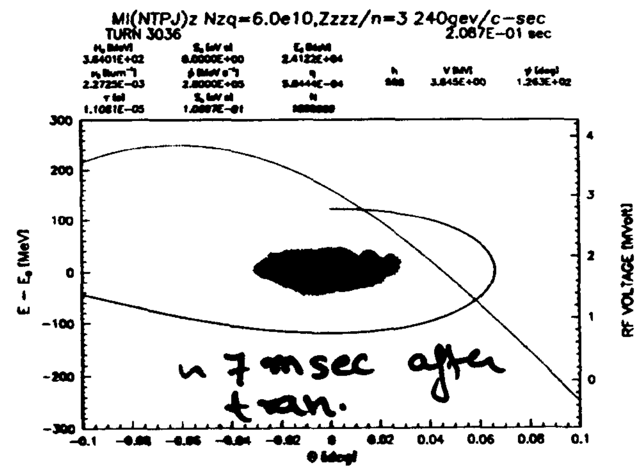


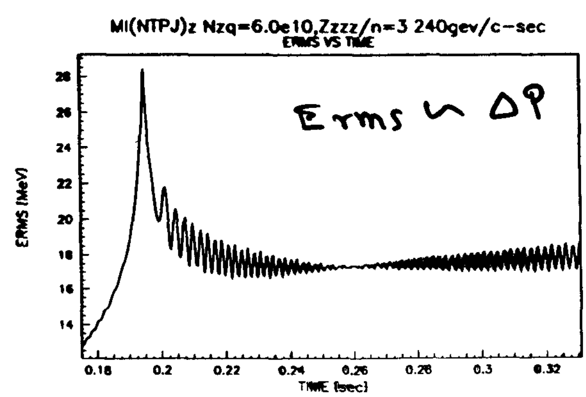


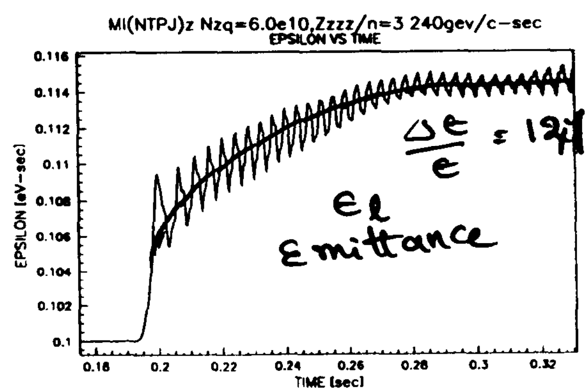
$I = 6 \times 10^{10}$ ppb

$Z/n = 3\,\Omega$, $\epsilon_l = 0.1$ eV sec. ; with Phase Feed back



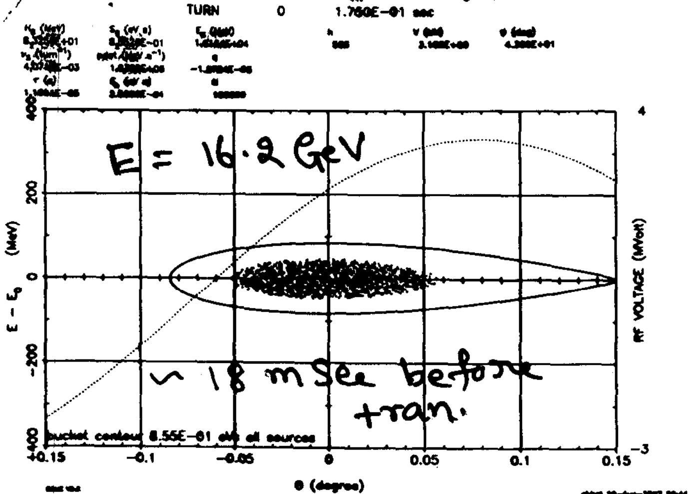




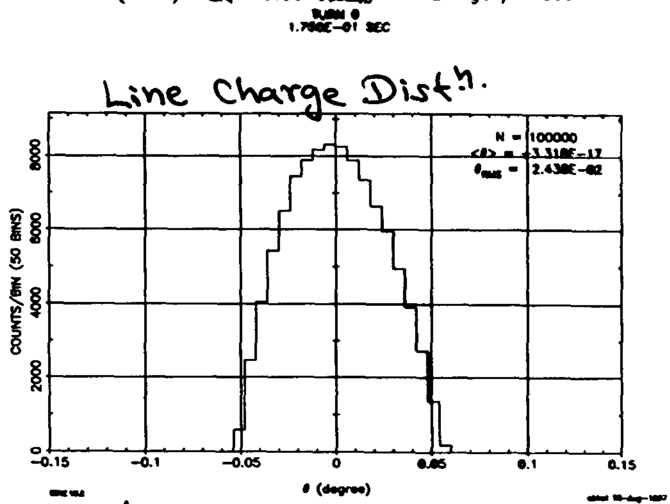


Calculations with 1997 Version of ESME

MI(NTPJ): N_q=15.0e10,Z_||/n=3 240gev/c-sec



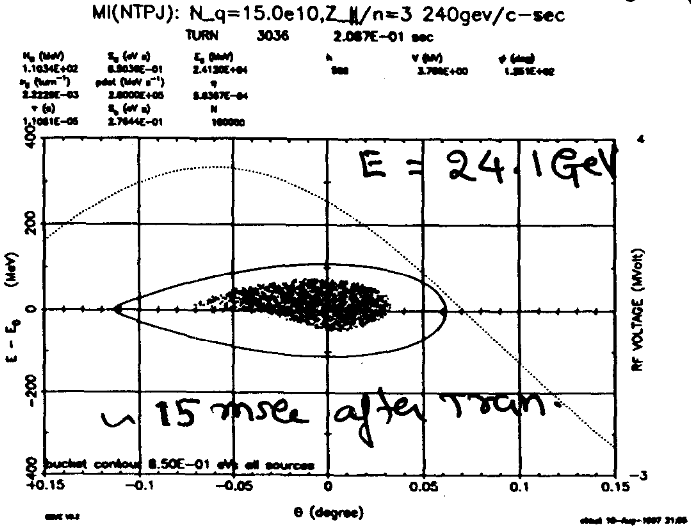
MI(NTPJ): N_q=15.0e10,Z_||/n=3 240gev/c-sec



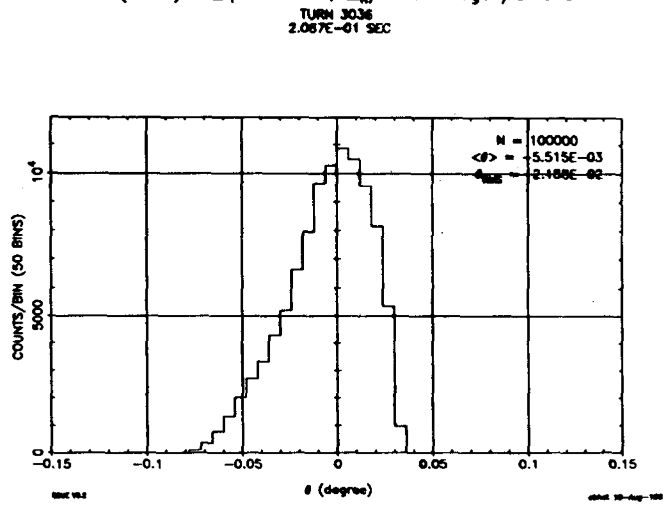
$I = 15 \times 10^{10}$ ppb $\quad Z/n = 3\Omega$, $\epsilon_L = 0.25$ eV-Sec.

No Phase Feedback

MI(NTPJ): N_q=15.0e10,Z_||/n=3 240gev/c-sec

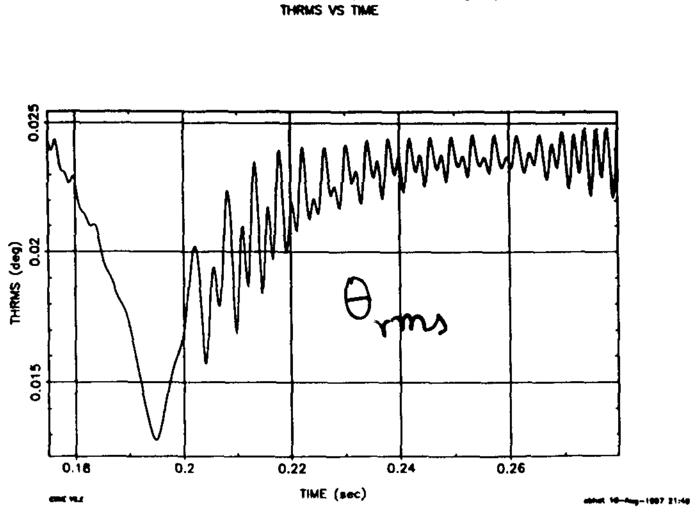


MI(NTPJ): N_q=15.0e10,Z_||/n=3 240gev/c-sec



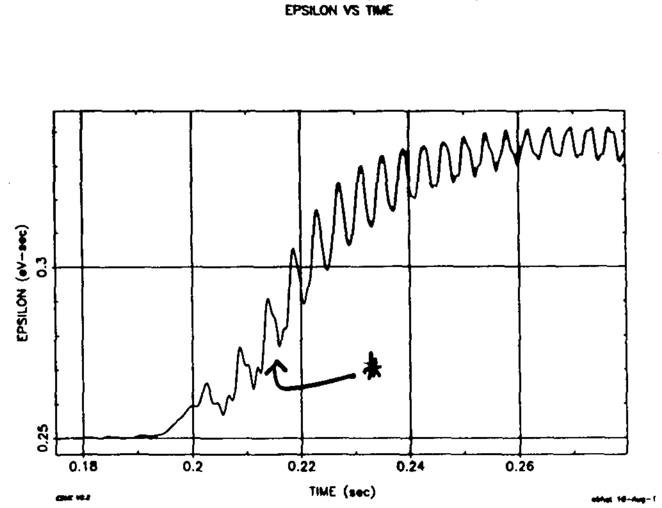
MI(NTPJ): N_q=15.0e10,Z_||/n=3 240gev/c-sec

THRMS VS TIME



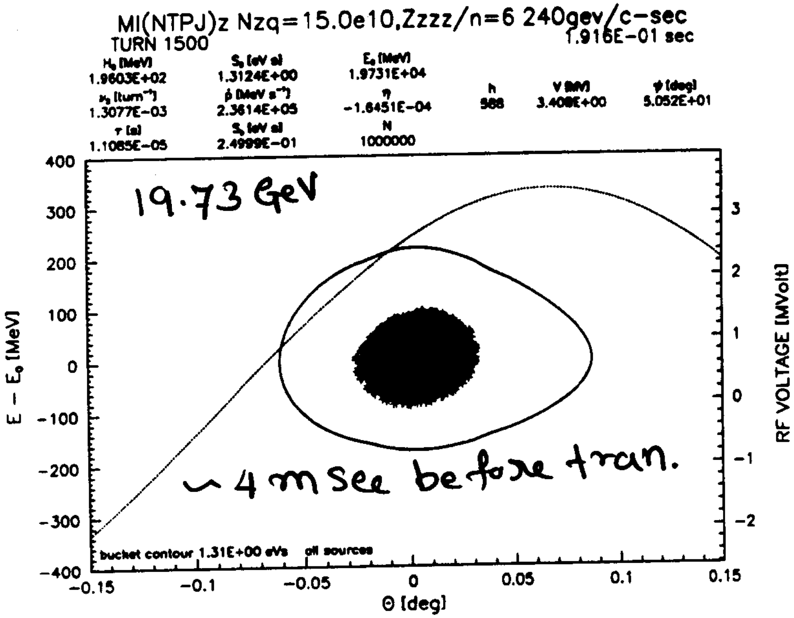
MI(NTPJ): N_q=15.0e10,Z_||/n=3 240gev/c-sec

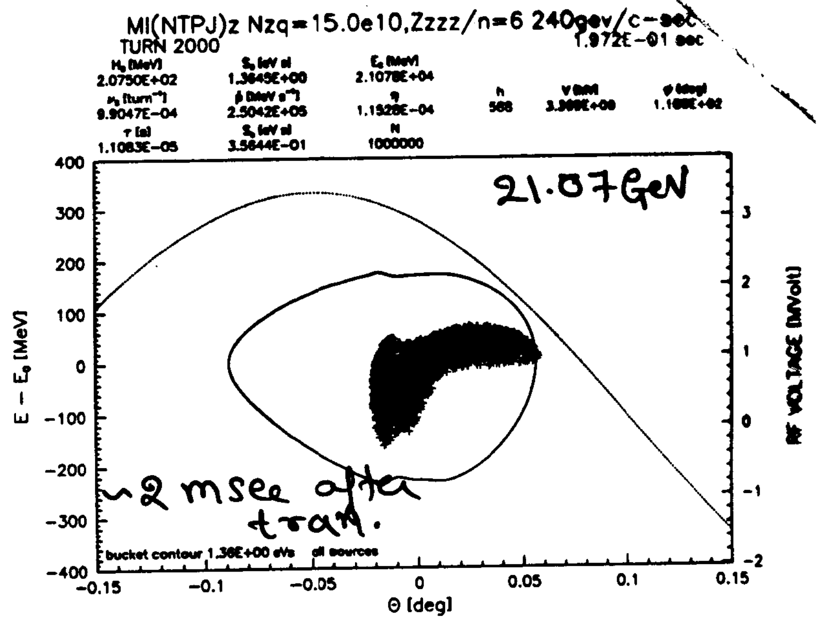
EPSILON VS TIME

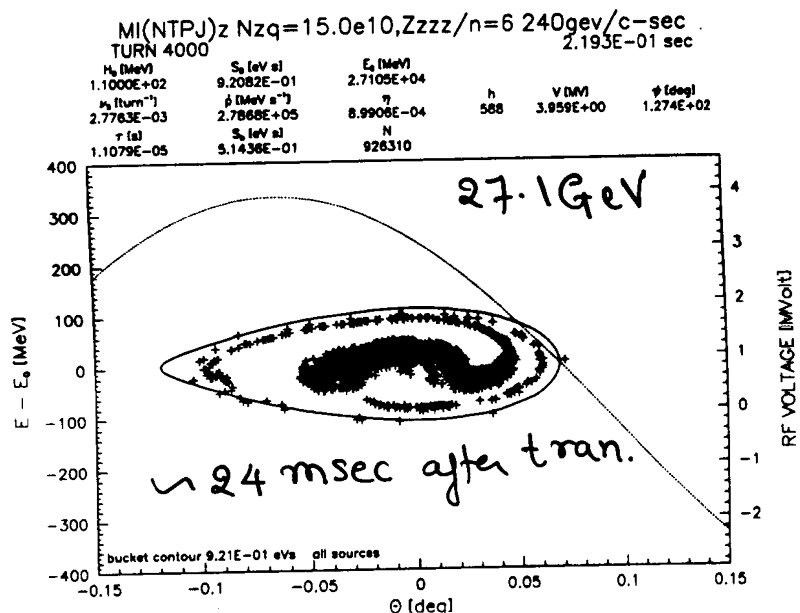


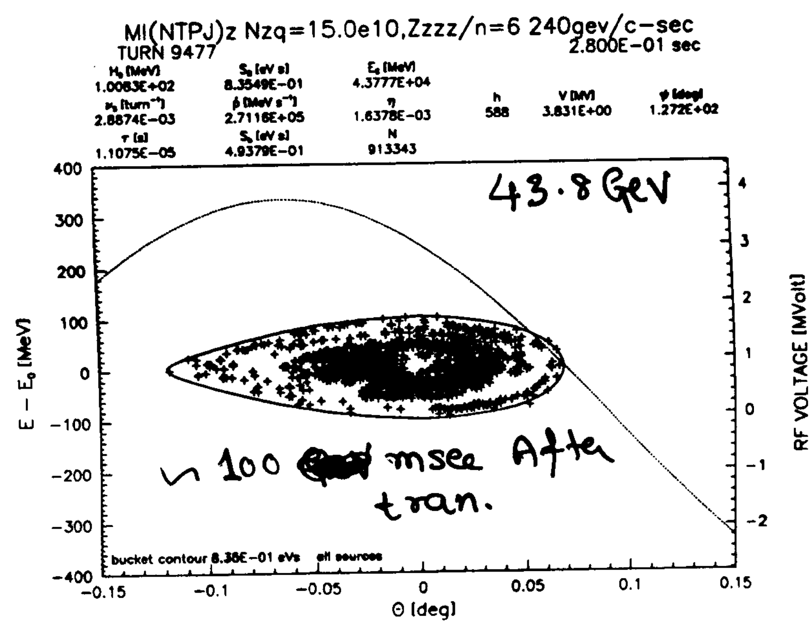
$I = 15 \times 10^{10}$ ppb

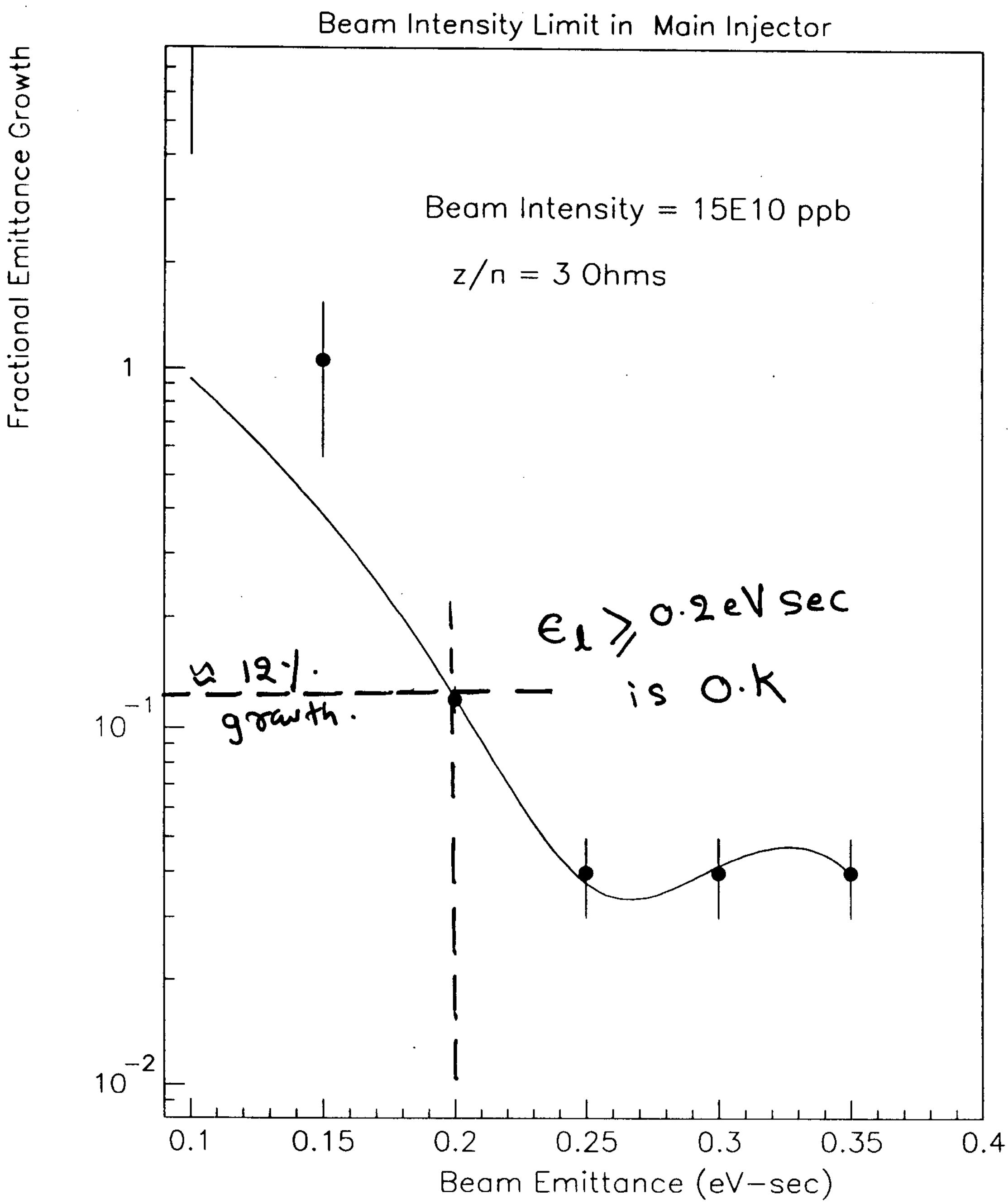
$Z/n = 6\,\Omega$ $\quad \epsilon_l = 0.25$ eV-sec.



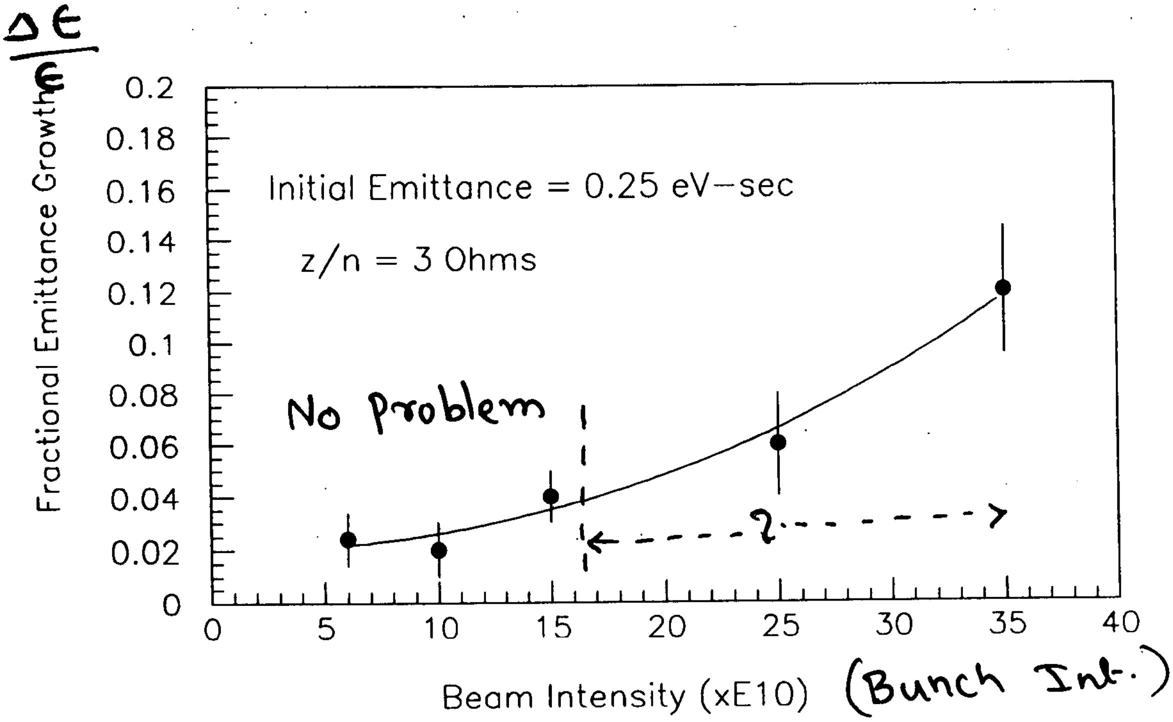




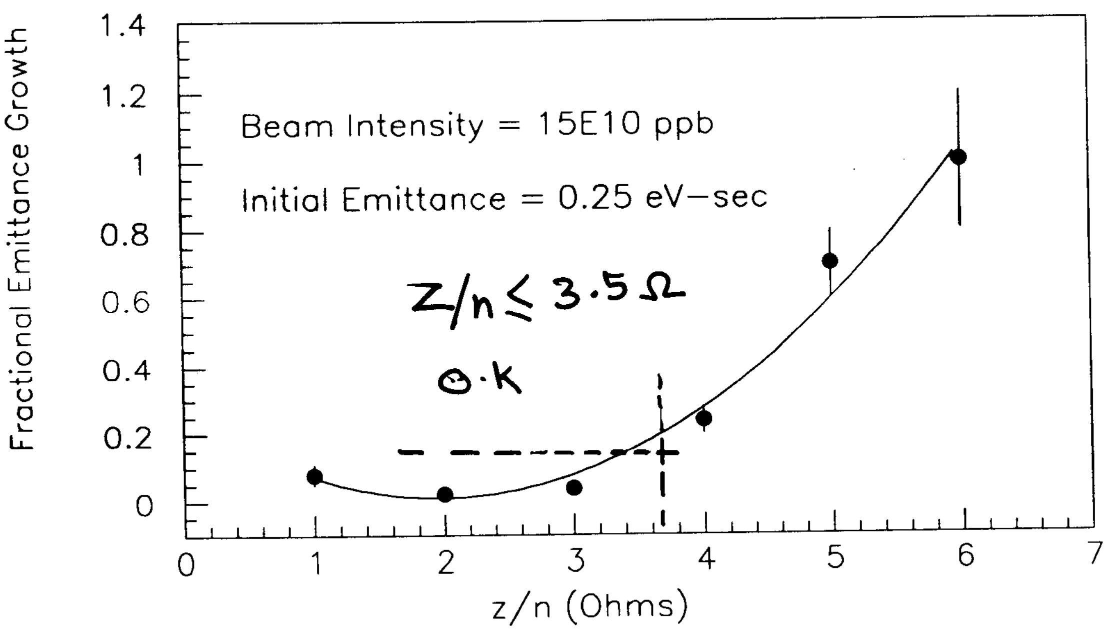




Beam Intensity Limit in Main Injector
Fractional Emittance Growth
Beam Emittance (eV−sec)
Beam Intensity = 15E10 ppb
z/n = 3 Ohms
1
10−1
10−2
0.1
0.15
0.2
0.25
0.3
0.35
0.4
≃ 12%
growth.
ε_l ⩾ 0.2eV sec
is O.K



$\Delta\epsilon/\epsilon$
Fractional Emittance Growth
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Initial Emittance = 0.25 eV-sec
z/n = 3 Ohms
No problem
?
0
5
10
15
20
25
30
35
40
Beam Intensity (xE10) (Bunch Int.)



Fractional Emittance Growth
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Beam Intensity = 15E10 ppb
Initial Emittance = 0.25 eV-sec
Z/n ≤ 3.5 Ω
O.K
0
1
2
3
4
5
6
7
z/n (Ohms)

Summary and Conclusions

\# We have studied the transition crossing problems for different operating scenarios of the Main Injector.
Suggestions were made to increase dp/dt from ~168GeV/c/sec to ~280GeV/c/sec to make transition crossing smooth.

\# Longitudinal beam dynamics simulations have been performed using ESME to estimate beam intensty limits through transition. The calculations were done including : a) **space charge effects** and b) **broad band impedance.**
We find that bunches with,

6×10^{10} ppb $\varepsilon_l \gtrsim 0.12$ eV-sec
10×10^{10} ppb $\varepsilon_l \gtrsim 0.20$ eV-sec <-- from s.s.
15×10^{10} ppb $\varepsilon_l \gtrsim 0.25$ eV-sec

can be accelerated with the **standard phase jump scheme** in the Main Injector

\# More calculations will be done with the time domain version of the ESME (being written by Jim).

\# There are number of issues to be addressed regarding acceleration of high intensity beam bunches in the MI. They are :

a) Coupled bunch instability excited by higher order modes in the MI (MR) rf cavities. This can be studied with ESME. Very important !!
b) Beam loading, RF power etc.